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Assessing the Use of Food Waste Biochar as a Biodynamic Plant Fertilizer

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Assessing the Use of Food Waste Biochar as a Biodynamic Plant Fertilizer

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An Honors Thesis
Submitted for partial fulfillment of the requirements
for graduation with honors in the
Biology Department and Program in Environmental Studies
from Hamline University

Spring 2016

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ABSTRACT

Biochar is a charcoal-like substance produced from plant material such as food waste. Converting food waste into a useful product would mitigate environmental damage through reduced landfill inputs, reduced greenhouse gas production, and increased benefits to soils. I asked (1) if biochar improved plant growth and (2) if the effects of biochar varied among different samples of mixed food waste (batches) and between different biochar preparation times (treatments). Four independent batches of biochar were prepared with assorted, uncooked food waste collected from a university dining facility. Each batch was dried then placed in a covered ceramic pot at 260°C for 3 or 6 hours under low oxygen (pyrolysis). Tomato plants (*Solanum lycopersicum*) were grown in soils with the eight batch-treatment biochar combinations or with no biochar (controls). Averaging over batches, the 3 and 6 hour treatments germinated significantly later than controls. Aboveground dry mass at 30 days did not differ significantly among the three treatments. Mean height growth rates (mm/day) were significantly higher in 3 and 6 hour treatments than in controls. Considering only biochar-treated plants, there was a significant interaction between pyrolysis time and batch for both germination time and height growth rate. Some batches germinated earlier when the biochar pyrolyzed for 3 hours was added, other batches when six hour biochar was added. Plants emerging later had faster growth rates, leading to no significant difference in size at 30 days. Both pyrolysis time and food waste source material had varying effects on plant growth. While biochar had no effect on mean dry mass at 30 days, complex effects on germination time and growth rate suggest that growing plants to maturity may lead to differences in plant size. Future studies should investigate effects of different food waste types on plant growth and assess nutrient content of source material.

INTRODUCTION

Biochar is an anthropogenic charcoal soil amendment that has the potential of addressing environmental problems such as soil degradation, food insecurity, water pollution from agrichemical sources, and even climate change by sequestering carbon in the soil for thousands of years (Renner 2007). When compared to other amendments, biochar has the potential to address many disadvantages of these and provide further benefits to the soil. Traditional fertilizer, when applied in proper amounts, can effectively provide necessary nutrients for otherwise limited plant growth. However, this synthetic nutrient addition can be easily over-applied and leach or runoff into the environment. These excess nutrients contaminate groundwater or cause eutrophication. Biochar can act as a slow-release fertilizer allowing for nutrients to be available only as the plants need.

There are many different amendments that are frequently added to improve soils, each of these has both benefits and drawbacks when compared to biochar. Similar to biochar, compost can also be applied to soils and has the benefit of using biomass that might otherwise be landfilled. Furthermore, compost has the advantage of providing a balance of nutrients in a low-cost amendment that can be made in-home. However, unlike biochar, compost can take months to properly age, though space for production can be a limiting factor for both. Similar to compost, manure takes 4 to 6 months to age for effective soil application. If applied fresh, manure can cause a nitrogen overload that severely harms plants. Additionally, it can contain diseases if not handled properly. Appropriately aged manure can provide many of the same benefits of compost.

Peat moss or coconut coir can also be applied and improve moisture as well as nutrient storage in sandy soils. However, unlike biochar, these do not support soil life and the production process for peat moss requires an entirely new crop of plants to be grown, though coconut coir is an agricultural byproduct. Biochar can be made from waste biomass, it can be produced relatively quickly on a small, in-home scale, and can improve microbial and mycorrhizal growth in the soil. Production at this individual household level could also reduce the transportation distance and emissions from use of other external fertilizer sources. Beyond these, biochar also raises soil pH, increases cation exchange capacity, and may adsorb heavy metal soil contaminants (these will be addressed in the following section). Yet, the energy to produce biochar and carbon released into the atmosphere through the high temperature production process might outweigh some of these benefits as well.

Biochar differs from charcoal because it is specifically produced to be used as a soil application to improve soil fertility and increase carbon sequestration (Budai et al. 2014). Produced in a process similar to common charcoal, biochar is used particularly for environmental purposes and refers to the biomass-derived black carbon. A

limited amount of oxygen is used to turn various types of biomass into char; this is then used for improving soil conditions, facilitating infiltration of pervading groundwater, and for carbon storage (Som et al. 2013). Lehmann et al. (2011) discuss the production of biochar as a thermal degradation process of organic materials in the absence of air, called pyrolysis. The most traditional feedstock for biochar is any woody biomass consisting primarily of cellulose, hemicelluloses, and lignin (Som et al. 2013). Feedstock selection should be done carefully, taking into account the end-use of the biochar. There is a notable difference in the chemical and physical properties of biochar made from materials of different stages of growth and type as well as in differing production methods.

Biochar is not a novel soil amendment. The peoples of the Amazon basin, circa 450 C.E. practiced a type of agriculture referred to as “slash-and-char” agriculture (Cox 2010). They would go through the process of roasting various kinds of wood and leafy greens in smothered fires. This resulted in fires with low temperatures and oxygen levels producing charcoal instead of ash; that charcoal, or biochar, was then buried in crop fields. In the 20th century, vast expanses of black soil were rediscovered, but not understood to be human-made until about 1990. These rich black soils were known as *terra preta de indio* and were found almost exclusively in the Amazon region where they were producing high crop yields in areas when the surrounding soils were poor (Renner 2007). The history of biochar is long, but much has yet to be learned about the production, use, and possible benefits of biochar.

First, a few of the uses and benefits of biochar will be discussed, I will move into the various biochar production methods, then cover the purpose and significance of this study.

Uses and Benefits

Studies have looked into the potential uses of biochar and to what extent it can benefit the environment. Of the many benefits biochar may offer, one is its use in increasing food production through improved soil conditions and fertility. Crops of corn and sugarcane grown in poor soils in Indonesia, the Philippines, Australia, South America, and Asia had increased yield with application of biochars (Renner 2007). Biochar, when used as a simple soil amendment, may have the ability to double or triple yields. Some crops have been found to grow as much as 45% greater biomass in unfertilized soil with biochar versus soils that have been fertilized with chemical fertilizers (Cox 2010). This may stem from the ability of biochar to increase the nutrient holding capacity of the soil and dole these out at rates optimal for growth. Budai et al. (2014) found an overall increase in biomass production as well with biochar added to agricultural soils. When averaged over two types of soils, Wang et al. (2012) found biochar amendments increased the production rates of rice and wheat by 12% and 17%, respectively. They postulated this particular increase could be attributed in part to increases in soil nitrate retention rates.

There are other agronomic benefits of biochar including water retention, nutrient retention, and the ability to remove heavy metals from soils and contaminated groundwater. These functions arise from the physical properties of biochar: high surface area, high pH, and the potential to increase cation exchange capacity of the soils (Budai et al. 2014). Also, as a highly porous material, biochar is found to increase the water-holding capacity of the soil and affect the microbial environments as well. Lehmann et al. (2011) found the observed effects of increased soil fertility can be explained by the increase in pH in acidic soils and improved nutrient retention. Further, Som et al. (2013) reported biochar was able to immobilize and retain heavy metals such as copper, arsenic, cadmium, and zinc. Addition of biochar also reduced the bioavailability of lead, which gives biochars potential mitigative qualities for contaminated soils (Som et al 2013). Budai et al. (2014) found that, in general, both properties of high-pH and cation exchange capacity work to influence the total availability of nutrients to soil microbes and plants. This makes biochar a candidate for high-value fertilizer that does not leach nutrients and can be made catered to the specifications of the crop being grown.

Another purported use of biochar is reclaiming degraded rangelands. Rangelands are widely used and pervasive throughout the globe. Savanna, grassland, shrubland, and desert biomes together comprise approximately 50% of the terrestrial surface of the world (Stavi 2012). Africa, Asia, and Latin America have 240, 200, and 110 million hectares, respectively, that are degraded. Globally, degradation occurs due to many causes including climate change, unsound practices in resource management, erroneous policies and regulations, a lack of enforcement, and political instability (Stavi 2012). The ability of biochar to fertilize and increase crop yields may help to curb some of the degradation and bring these rangelands back inside safe parameters of use.

However, there are some challenges to using biochar as a method of reclaiming degraded rangelands. The main challenge is the low availability of biomass in these areas that can be used as feedstock for production. One potential feedstock available in these areas is manure collected from livestock pens (Stavi 2012). Manure-based biochars can increase the overall nitrogen concentration of soils, as well as increase water conductivity of the soil and accessibility for the plant. The inert nature of manure-derived biochar allows it to behave as a means of larger and longer-term carbon sequestration, it is superior to raw manure applied as fertilizer in this way (Stavi 2012). The application of biochar in the soils of degraded rangelands throughout the world may considerably improve their carbon sequestration capacity as well. With 550 million hectares of degraded rangeland, assuming a carbon concentration in biochar of 50% and a minimal rate of application of 1 kg of biochar per square meter on 25% of the surface of the degraded rangelands in the world, the potential for carbon sequestration at this level is 690 teragrams

in rangelands alone. Biochar has been shown to have extreme importance and potential for use in reclaiming degraded rangelands.

Other issues related to global climate change and anthropogenic environmental problems may have the ability to be curbed through the use of biochar. In both developed and developing countries, extensive groundwater contamination through nitrates that have been sourced to fertilizer use poses an increasing threat to human health. Also, nitrogen leaching and loading in waterways and runoff from agricultural fields contributes to the worsening eutrophication in lakes, oceans, and streams. Guereña et al. (2013) found the nitrogen leaching losses have been greatest in maize-based cropping systems. Several diets internationally depend on maize cultivation. These losses from the system inherently exemplify the inefficiencies in the way nutrients are mismanaged resulting in not only additional costs to farmers but also environmental pollution and damage. The use of biochar may help to reduce this problem. Cayuela et al. (2013) found biochar had a significant impact on denitrification with a consistent decrease in nitrous oxide emissions by 10-90% in 14 different agricultural soils. Addition of biochar to soils in tropical regions has reduced nitrogen leaching and has been able to increase nitrogen use and efficiency. However, Guereña et al. (2013) found biochar added to fertile soil in more temperate climates did not improve crop growth or nitrogen efficiency and only moderately increased topsoil retention of fertilizer nitrogen. Also, though the biochar did reduce total nitrogen losses from leaching, this was found only at high rates of nitrogen fertilization.

Biochar has also been recognized as a soil amendment with the ability to take up ammonia. Taghizadeh-Toosi et al. (2012) found that biochar-adsorbed ammonia is bioavailable. Nitrogen adsorbed by biochar in the form of ammonia was stable in ambient air, but when placed in soil was readily bioavailable (Taghizadeh-Toosi et al. 2012). The recovery of the nitrogen isotope in the plant tissues was found to range from 29 to 45% of the total isotope applied. Therefore, human-produced ammonia emissions have the potential to be captured using biochar as a soil amendment then made bioavailable. This would aid in nitrogen capture by crops leading to the need for less fertilizer in the long-run.

Biochar application has also been found to be a powerful tool for mitigating climate change through carbon sequestration. The process of pyrolyzing biomass to produce biochar takes carbon out of the air and locks it in the porous product (Renner 2007). As plants grow they take up CO₂, after pyrolysis only a small amount is released and the rest is able to be sequestered in the biochar product making the net process carbon negative. Renner (2007) reports even after adjusting for processing emissions, the production of biochar from waste biomass could have the potential to sequester 20 to 50% of the carbon originally held in the biomass.

Many studies claimed biochar production and use as a soil amendment may have the ability to act as a long-term sink for atmospheric CO₂ (Budai et al. 2014; Cao and Harris 2010; Lehmann et al 2011; Liao et al. 2013). This property stems from its resistance to microbial degradation and decomposition, yielding the ability to very slowly return organic carbon to the atmosphere. Wang et al. (2013) found this potential is due to the higher carbon content of biochar and its ability to withstand longer durations in soils than ordinary biomass. If all discarded plant biomass was completely converted to carbon-rich and environmentally-stable biochar, the hypothetical potential of net carbon withdrawal from the atmosphere might be as high as 24 gigatons of carbon per year; this is 20% of the total CO₂ captured through photosynthesis (Wang et al. 2013).

More than just CO₂, however, biochar production has been found to have the potential to decrease emissions of other noxious greenhouse gasses. Renner (2007) discusses how both nitrous oxide and methane might be able to be reduced when otherwise decomposing biomass is made into biochar. Nitrous oxide is several hundred times more potent of a greenhouse gas than CO₂ and methane is 21 times more potent. Emissions of nitrous oxide were reduced by 80% and methane emissions were entirely contained in both greenhouse and field experiments in Columbia (Renner 2007). However, further investigation is needed on this potential effect of biochar use because Wang et al. (2012) found the addition of biochar to certain soils actually increased methane emissions by 37% during the rice season but had little effect in the wheat season. Biochar decreased nitrous oxide emissions by up to 54% during the rice season and 53% during the wheat season (Wang et al. 2012). So, though it may have potential as a nitrous oxide reducer, biochar may prove to be less useful as a methane gas reducer in the environment. More investigation is needed before this claim of greenhouse gas reduction can be made.

Biochar Production

Pyrolysis is used for biochar production and is a thermal treatment of biomass under the presence of limited or no oxygen (Budai et al. 2014). Pyrolysis works to turn the biomass into biochar through successive chemical reactions induced by heat treatments. These reactions include cleavage and polymerization of the feedstock. Many factors influence the extent of the reactions such as pressure, carrier gas composition, energy supply rate, and certain catalytic inorganic impurities. Sun et al. (2014) found there are differing effects in the biochar product made with different feedstocks, production methods, and temperatures. Biochars that were made at lower temperatures had higher production rates, whereas higher temperatures increased carbon content of the product and produced biochars with higher thermal stability (Sun et al. 2014). Thermal stability is a quality that means the product does not decompose in open air after temperatures in the 400-450°C range. Ultimately, Sun et al. (2014) found biochars with

different properties can be developed to target specific environmental applications by changing the production conditions.

Feedstock type has been considered in a number of studies and each has found variation in biochar properties depending upon individual type. Bird et al. (2011) used algae in a study advancing the use of algae as a suitable and environmentally-sound biochar feedstock. Algae have a number of different characteristics that make them valuable for biochar feedstock (Bird et al. 2011). They are generally fast growing and are widely available from systems where they are already considered a pest species. Some species are given the colloquial name “green tide” because they take over ecosystems and can thrive in water of almost any salinity and nutrient composition. Some of the algae genera used are *Cladophora*, *Chaetomorpha*, *Rhizoclonium*, and *Ulva*. One last characteristic valued in algae as a prime biochar feedstock is their ability to assimilate nutrients like nitrogen and potassium and sequester heavy metals (Bird et al. 2011).

The properties found in the algae-based biochar varied from other feedstock types (Bird et al. 2011). The product was low in carbon content but was high in nitrogen compared to lignocellulosic biomass (i.e. sugarcane, poplar trees). The average carbon content for the algae-based biochar produced was 23%; this gives a carbon sequestration potential calculated for an average agricultural operation to be approximately 500 tons of carbon dioxide per year. Also, when compared to the terrestrial biochars, the algal biochars had high electrical conductivity, pH, and extractable phosphorus. In all, Bird et al. (2011) found algae from aquaculture wastewater and from eutrophied natural bodies of water is a suitable option for biochar feedstock applied as a soil ameliorant and as a means of carbon sequestration.

Another feedstock studied for use in biochar production, dairy manure, is a biomass widely available and largely considered to be waste. More than 300 billion pounds of dry dairy manure are produced every year in the United States alone, yet this waste is high in many nutrients including nitrogen and phosphorus (Cao and Harris 2010). Manures are often applied to fields as inexpensive and natural fertilizers; dairy manure is frequently used for this purpose. However, this application has high risk of runoff and nutrient leaching which jeopardizes the water quality of surrounding lakes and streams. There is a demand for environmentally beneficial uses for livestock manure that helps to alleviate these and other waste management issues. Cao and Harris (2010) investigated the use of dairy manure for the purposes of biochar production. Biochar from dairy manures of different kinds, from separate farms with differing diets, all behaved similarly. Dairy manure biochar was produced with low heat pyrolysis using temperatures less than or equal to 500°C with abundant air. The characterization of physical,

chemical, and mineralogical properties implicated the successful use of biochar for remediation of environmental damage from other fertilizer types. This biochar was found to be rich in sodium, calcium, magnesium, potassium, and carbon. The surface area, ash content, and pH of the dairy manure-derived biochar all increased as the temperature increased, but the yield of the biochar material decreased as well (Cao and Harris 2010). The combustion and volatilization caused the carbon and nitrogen content to decrease with increased temperatures.

Cao and Harris (2010) also found dairy manure biochar had the ability to absorb lead from aqueous solutions. The biochar absorbed up to 100% of lead content. Dairy manure biochar may be able to be used as an effective means to absorb lead and possibly other heavy metals from ecosystems in need of remediation. Further, Cao and Harris (2010) found lower temperatures, under 350°C, resulted in partial combustion which yielded biochars with high pH. This is a characteristic that may make this particular biochar useful as an amendment to neutralize soil acidity. Finally, the lower temperatures gave the biochars the potential to have a reduced phosphorus solubility (Cao and Harris 2010). This product has a possible use as a slow phosphorus-release fertilizer. This could simultaneously improve crop production, yet limit the leaching of the excess phosphorus into water sources from the direct use of raw manure. It should be noted that biochar previously used to remediate soils may not be beneficial for further use as a fertilizer in soils; more studies are needed for the investigation of this application. Many other manures could be investigated as a feedstock for biochars that may work to remedy current environmental conundrums, but dairy manure has been found to be a potential excellent source for biochar feedstock biomass.

Palm fronds have also been investigated for use in biochar production. The main use of the palm tree, extraction of palm oil, has been the primary source of oils and fats for ten years around the world (Som et al. 2013). In 2009, there was more than 45 million tons of palm oil produced globally. The country of Malaysia alone has over 45 million hectares of land planted with oil palm and more than 300 palm fronds are pruned per hectare per year. This makes palm fronds a very abundant, useless byproduct of palm oil currently either being used as roughage feed, or, more often, left between the rows of palm trees to prevent the process of soil erosion. Biochar production has been proposed as an alternative use for these abundant palm fronds. Som et al. (2013) studied a biochar production and carbonization method traditionally used by gardeners in Malaysia to improve soil fertility. This involved digging a shallow earth pit for the location of the carbonization process. The heat and soot from the burning of the palm fronds in the earth pit changed the pH levels and the organic content of the soil around the pit resulting in this sample being more fertile compared to pre-existing soil.

Som et al. (2013) also found the biochar produced in this method had many mesopores (pores with diameters between 2 and 50 nm) that may prove useful for adsorbing organic pollution as well as heavy-metal contaminants. As with other biochars, this biochar may be useful as an effective source of slow-release fertilizer in tropical areas with high rainfall because of the high amounts of soluble potassium in the biochar product (Som et al. 2013). Biochar production could then prove very useful for the consumption of these abundant palm fronds and also help improve soil quality and the environment.

A final feedstock studied for possible use in biochar production is invasive plant species. The production of biochar is beneficial to the environment in a number of ways, but using non-native, invasive plant species in particular locations would also be advantageous to ecosystems inundated with such species. The exceedingly rapid spread of invasive species has posed an increasing threat to natural ecosystems of all kinds throughout the world; these invasive plant species also bring risks to public health and economies. Unfortunately, the removal of these invasive plants involves methods costly to both the economy and the environment. Usually, mechanical means (i.e. pulling and digging) or chemical means (i.e. herbicides) are needed to remove invasive species, and these need large capital and human investments. The application of chemicals has unintended risks for native species and public health.

Liao et al. (2013) studied the use of two main invasive plant species as feedstock for biochar and bioenergy through the process of pyrolysis. Brazilian pepper and the air potato were used as the invasive feedstock and each were compared to two traditional feedstocks: water oak and energy cane. Both the Brazilian pepper and the air potato are among the most invasive and destructive plant species in the Southeast United States region. Liao et al. (2013) found the air potato had a higher biochar yield than the Brazilian pepper, but the Brazilian pepper had a higher bio-oil yield (bio-oil is a potential fuel source). Also, both of these plants have very similar biochar and bioenergy yields to that of traditional feedstocks and can be used as viable biomass for biochar production (Liao et al 2013). These findings are important because they indicate how pyrolysis can be a cost-effective and alternative strategy for managing these and other invasive plant species globally. If prolific, invasive species can be turned into biochar, then this otherwise waste biomass can be used to create a beneficial soil amendment. This would provide a financially expedient management strategy since it does not require dependency on other means of disposing the invasive biomass.

Project Purpose and Significance

My study examined the use of food waste as the feedstock for biochar. Previous studies have not investigated the use of mixed food waste from a market or family kitchen, as feedstock for biochar and have not assessed the use of this biochar as a fertilizer for comestible plant growth. Chen and Chen (2009) dried orange peels as feedstock for biochar using a laboratory oven to pyrolyze the food waste. My study used mixed food waste sourced from university dining services pyrolyzed at conventional home oven temperatures. This “in-home” method was studied because a more accessible method would allow for the production of biochar on a small scale. Although industrial methods of mass producing biochar may be possible and ultimately beneficial, production on a smaller scale or in areas of developing countries would allow for fulfilling the demand for high-quality, economically-feasible fertilizer. Since food waste will never be completely eliminated, converting it to a useful product would both reduce environmental damage and provide other benefits.

Global urban food waste is predicted to increase up to 44% by 2025 (Adhikari et al. 2006). Hall et al. (2009) found food waste has already increased by approximately 50% since 1974. On an agricultural scale, 1.3 billion metric tons of food is lost each year with a direct economic impact of \$750 billion annually (UN FAO Report 2013). This translates into more than 1400 calories per person per day or 150 trillion calories per year in waste that would otherwise go into landfills (Hall et al. 2009). Landfill gases are a major source of anthropogenic methane emissions, in large part due to food waste. For every ton of food waste put into landfills, 125 cubic meters of greenhouse gas is emitted (IPCC 2001). Of this, 60-65% is methane and 35-40% is carbon dioxide. Landfills in countries with a higher GDP are responsible for 30-37% of total anthropogenic methane emissions in the world (US EPA 2003).

Adhikari et al. (2006) found that if current waste management trends are maintained indefinitely, urban food waste put into landfills would increase global methane emissions from 34 to 48 grams of pollutant per kg of dry waste. Also, under current trends, there will be an increase in the share of anthropogenic emissions from landfills from 8 to 10% (Adhikari et al. 2006). A UN Food and Agriculture Organization report (2013) found the cumulative effect of food waste has significant impact on biodiversity, land and water use, and especially global climate change. It is because of these negative impacts and contributions of food waste to environmental degradation that this study is needed. Alternative methods for the efficient and effective use of food waste are critical in working to mitigate and limit future impacts of food waste on the biosphere. The goal of my study was to examine a productive use for food waste, which could limit the amount added to landfills and therefore limit the production of greenhouse gasses. There is a vital need for research into environmentally-friendly, efficient uses of food waste.

These methods could provide families or small businesses with a means of upcycling their food waste into a useful and potentially profitable product.

The specific questions I addressed were: (1) Can effective biochar fertilizer be made from food waste? and (2) Does the effect of biochar vary among batches of food waste or pyrolysis time?

I produced biochar from food waste and assessed how effective it was as a fertilizer via a tomato (*Solanum lycopersicum*) growth assay. I recorded the germination date and took growth measurements of the plants. The growth rate of the plants was also obtained from plant height measurements, at each day of data collection, in millimeters of growth per day. The individual batches and separate pyrolysis times were also assessed in the same growth assay and compared to each other.

Germination time can be used as an effective measure to test biochar quality (Sun et al. 2014, Rogovska et al. 2012, Solaiman et al. 2012, Free et al. 2010). Several studies have found there is no effect on seed germination with application of biochar (Sun et al. 2014, Rogovska et al. 2012, Free et al. 2010). Seeds in biochar amended soils should germinate at the same time as seeds in control soils if the biochar product is of high quality. Changes in biochar application rates, soil type, and biochar feedstock type all have negligible effect on seed germination time. However, some increase in seed germination has been seen at low rates of biochar application; this effect is not seen in very high application rates (Solaiman et al. 2012).

Improvements in soil nutrient availability and increases in pH demonstrate how biochar can increase plant growth rate and overall health (Guereña et al 2013, Som et al. 2013, Lehmann et al. 2011, Bird et al 2011, Cao and Harris 2010). Some growth benefit is due to the ability of biochar to release nutrients as-needed for plant growth (Budai et al. 2014, Liao et al. 2013, Lehmann et al. 2011). Improved nutrient retention and increases in cation exchange capacity of biochar-amended soil also benefit plant growth. With more available nutrients, biochar-amended soils should have larger and faster growing plants.

Aboveground dry mass of plants grown in biochar has been found to be less than the belowground biomass allocation (Muller et al. 2000). Some reduced aboveground biomass allocation was found to occur in low-nutrient soils. Since plants respond to a lack of available belowground nutrients with increased root biomass allocation, less energy and resources are allocated to aboveground development (Poorter and Nagel 2000). When compared with a low nutrient soil, and if biochar does increase nutrient availability, the biochar amended soil should produce plants with greater aboveground biomass. Due to the high surface area of biochar particles, they have a highly porous nature allowing for improved water-holding capacity of the amended soils (Budai et al 2014). This ability allows for

a flourishing of the soil microbial population and stimulates mycorrhizal growth in biochar amended soils (Budai et al. 2014, Cox 2010, Lehmann et al. 2011, Bird et al. 2011, Renner 2007). All of these various properties have been found to improve plant growth with the addition of biochar to the soil.

I predicted biochar would not have an effect on germination. Germination time is affected mainly by moisture and temperature. With both of these held constant between the control and biochar plants, no effect of biochar on germination was expected. In the other growth measurements, I expected biochar amended plants to surpass the control plants. As an effective fertilizer, biochar should increase plant height, leaf canopy diameter, and leaf number, as well as improve the final aboveground dry mass when compared to the control plants. Growth rate of the biochar plants was also expected to be higher than the non-biochar amended plants.

MATERIALS & METHODS

Food Waste Material

I used the methods of Chen and Chen (2009) as a guide for this study. Uncooked and unprocessed mixed food waste was collected by hand from the Hamline University dining facility kitchen. I chose food waste from kitchen food preparation scraps. No special consideration was taken in gathering the material for each of the four collected volumes of food waste, here called batches; I selected only the most available food waste in the bin at the time of collection (images available in Appendix). Each batch was collected independent of the others. Processed or cooked food waste was not obtained; I avoided these foods to eliminate the addition of other substances (i.e. salt, oils, etc.) to the soil. I recorded source food waste components of each batch in order of decreasing abundance (Table 1).

Biochar Production

I collected enough food waste for 0.5 L of biochar per batch in order to get the required mixing rate of 5% by mass biochar in the soil (Chen and Chen 2009). Based on preliminary studies, a 2:1 fresh food waste to pyrolyzed biochar product ratio was expected. So, I collected around two liters of food waste for each batch to ensure production of sufficient amounts of biochar. I processed the food waste using the same methods for each batch, differing only in pyrolysis length. I hand-chopped each batch of food waste into pieces smaller than approximately three cm. This chopped food waste was air dried in a greenhouse for two days. I set each batch in trays and covered them with a fine mesh to prevent insects from reaching the drying food waste. I oven dried the batches overnight for 12 hours in a Fisher Scientific Isotemp 725g Laboratory Oven at 75°C. The oven-dry mass and volume was recorded for each batch. For pyrolysis, I put the entire batch in a glass-lidded, CorningWare French White Round 2.3 L ceramic casserole dish and cooked at 260°C in the same oven type and model as above. I removed half of the volume after three hours while leaving the other half in the oven to pyrolyze for six hours. I made four different batches of biochar using these methods; each of those four was separated only at the pyrolysis stage into three hour and six hour subdivisions. Pyrolyzed biochar was ground in an Osterizer Imperial Cycle Blend Pulse-Matic blender on high for approximately 15 seconds per batch until it became a fine powder.

Growth Assay

Plants were grown in nine cm square pots in a greenhouse with daily watering on a timer for 30 days. Two hundred and four tomato plants (*Solanum lycopersicum*) were grown in low-nutrient Pro-Mix All Purpose Growing Mix. These seeds were used following the growth assay methods of Graber et al. (2010) of tomato plants in biochar.

I added biochar at a rate of 5% by mass to each of the test pots (~20mL) using a small measure leveled at the top, and mixed into the upper one inch of the growing mix (Graber et al. 2010). For each of the four batches 17 plants were grown and measured with the three hour biochar amendment and 17 plants with the six hour biochar amendment (Table 2). Sixty-eight control plants were also grown to correspond with the plants in the three and six hour treatments. Control plant growth was carried out in the same manner as the test plants in the Pro-Mix All Purpose Growing Mix without biochar added to the soil.

Plant Measurements

I recorded germination date as the day the first seedling shoot emerged visibly above the soil for each plant. Several plant growth measures were recorded every 6 days: plant height, leaf number, and maximum leaf canopy diameter. Plant height was measured in cm from the base of the aboveground stem to the highest leaf point on the plant. Leaf number was recorded as the total number of leaves that met or exceeded 10 mm in length. Maximum leaf canopy diameter was measured in cm as the furthest distance from end to end of the leaf extensions on each plant (Fig. 1). At the end of the 30 day growing period, total aboveground dry mass was measured for each plant. Growth assay was stopped at 30 days because the plants would have needed to be grown in larger pots or transferred at this point and growth space was limited. Dry mass was obtained by cutting the plants off at the base of the aboveground stem and drying the plants overnight at 105°C in a Fisher Scientific Isotemp 725g Laboratory Oven. The dried plants were then weighed individually and the dry mass recorded in grams for each plant. Belowground root biomass was not collected due to time restraints but would also be useful in assessing overall plant growth. Time as well as space prevented growing plants to maturity. Heavily root-bound plants such as tomatoes would need to be grown in much larger pots to allow for full plant growth and fruit-bearing.

Statistical Analyses

Analysis was done using R statistical package (R Core Team 2015). My two questions led to an experimental design that required two separate analyses. The first question was “Can effective biochar fertilizer be made from food waste?” To investigate if biochar had an effect on plant growth when compared to untreated plants, I compared three hour biochar, six hour biochar, and control means using one-way analysis of variance (ANOVA) or a Kruskal-Wallis Test. Sample sizes for these comparisons are indicated in the far right column (Treatments) in Table 2. Since there were no corresponding control batches with which to compare each of the biochar batches for analysis purposes, individual batches were not considered in this analysis.

The second question was “Does the effect of biochar vary among batches of food waste or pyrolysis time?” To address batch consistency and variation in pyrolysis time, a two-way factorial ANOVA was used and controls were excluded. These sample sizes are indicated in the (Batch) columns 1-4 in Table 2. Controls were not used in these analyses because there were no analogous batches of controls against which to compare the biochar batches.

ANOVA assumptions were examined using box plots, quantile-quantile plots, and Levene’s Test for homogeneity of variances. I transformed data to better match ANOVA assumptions if not normally distributed or if there were unequal variances for the different groups. The emergence date, final dry mass, and growth rate by batch data were natural log transformed to improve their normality. Once assumptions were met, I computed the ANOVAs using Type II sums of squares due to unequal sample sizes. ANOVAs for emergence date by batch and treatment, final dry mass by batch and treatment, growth rate by batch and treatment, as well as emergence date by treatment were computed using R package DescTools (Signorell et al. 2015). One-way nonparametric tests of equality of means were computed using the Kruskal-Wallis Test. A Kruskal-Wallis test was used for both emergence date and final dry mass because the variances of the groups were significantly different according to the Levene’s Test performed. The Kruskal-Wallis test compares the medians, not means, but means will be used for consistency in data visualization.

Nutrient Tests

Soil nutrient tests were done on the Pro-Mix All Purpose Growing Mix (control) and all four batches of the three and six hour biochar products using a LaMotte Soil Analysis Kit (Model no. 5008). A biochar/soil mix was not tested because the mixing rate was so low, and the suspension of the biochar/soil mix was not able to be prepared. Nutrient content in parts per million (ppm) for chloride, phosphorus, nitrate nitrogen, potassium, and nitrite nitrogen, as well as pH of each batch and treatment were determined.

RESULTS

Batch Contents and Nutrients

Batch 1, consisting mostly of cauliflower stems and pineapple rinds and tops, air dried quickly and oven dried into crisp pieces before being pyrolyzed. These pre-pulverized charred pieces were very dry and visibly porous. Batch 2, mostly watermelon rinds, was much harder to air dry; only after oven drying this batch was there enough moisture driven off for pyrolysis. The post-pyrolysis pieces were not as dry and porous as those from batch 1. Batch 3 contained a mix of equal parts potato peels, pineapple cores, and cantaloupe rinds. The air drying of batch 3 went as poorly initially as batch 2, but dried well in the oven. Finally, the batch 4, of almost entirely carrots, was the most difficult to dry. After being air dried and oven dried the batch was still quite moist and not crisp pieces as the other batches had been. It was pyrolyzed under the same conditions as the other batches, but the final product was not as crisp or porous as the others. This meant that the fourth batch was harder to pulverize in the final production step. There were no significant differences found between the biochar treatments or batches in nutrient content (Table 3). In comparing the nutrient content of the three and six hour treatments, the following statistical results were obtained: chloride ($p=0.083$); phosphorus ($p=0.157$); nitrate nitrogen ($p=0.564$); potassium ($p=0.564$); nitrite nitrogen ($p=1.0$); pH ($p=1.0$).

Emergence Date

The emergence date depended on which treatment the plant received. Control plants emerged significantly earlier than the three hour and six hour pyrolysis treatments (Fig. 2). Emergence was almost twice as early in the control plants at 1.36 (± 0.171) days on average than in both the three hour treatment, at 1.91 (± 0.303) days, and the six hour treatment, at 1.95 (± 0.361) days on average ($p < 0.0001$). There was significant batch by treatment interaction in emergence date when only the biochar treated plants were considered ($p < 0.003$; Fig. 3). For example, batch 4 plants emerged before day six in the three hour treatment but emerged on day ten on average in the six hour treatment. The effect of the biochar by batch cannot be distinguished without also discussing the treatment received.

Aboveground Dry Mass

When averaged over all batches, aboveground dry mass at 30 days did not differ significantly among control, three hour, and six hour treatments ($p < 0.71$; Fig. 4). Ignoring control data, there was marginal interaction between batch and treatment for final dry mass ($p = 0.065$; Fig. 5). Batches 1 and 2 had a larger final dry mass in the three hour treatment and a smaller final dry mass in the six hour treatment. Batches 3 and 4 showed the reverse, a smaller final dry mass at three hours and larger final dry mass at six hours.

Growth Rate

The slope of the height versus time regression was used for each plant as a measure of overall growth rate. Linear regression was used because it was the best fit for the data based on height of each batch versus days after planting for both the three hour (Fig. 6a) and the six hour treatments (Fig. 6b). Plant height was highly correlated with leaf canopy diameter and leaf number measurements and was used as a summary measure for growth rate (Fig. 7). Growth at each day of measurement was recorded and used to find the height growth rate in millimeters per day for each plant.

Mean height growth rates (mm/day) did not differ significantly among control, three hour, and six hour treatments ($p = 0.56$; Fig. 8). There was significant interaction between batch and treatment for height growth rate when controls were not considered ($p = 0.039$; Fig. 9). Batch by treatment effects interacted and quality of the batches cannot be determined without also specifying the treatment the batch received.

Growth rate was faster in the later emerging biochar plants. Some outliers were removed from the data to better indicate the overall trend. For the three hour treatment, one plant emerged very late and grew very slowly (Fig. 10a). This data point was removed and the data fit the regression line much more closely; there was an r^2 increase from 0.19 to 0.31 after removal of the outlier (Fig. 10b). In the six hour treatment, three plants varied greatly from the overall trend of the regression line (Fig. 11a). These three data points were removed and the coefficient of determination was again improved; the r^2 increased from 0.013 to 0.25 after removal of the outliers (Fig. 11b). There were no outliers in the control data and no control data points were removed for the analyses (Fig. 12). With the outliers removed from the three and six hour treatments, all regression lines graphed together (Fig. 13) displayed that the control plants emerged early and mostly together where the three and six hour biochar plants emerged over a wider range of days. The relationship of natural log of emergence date and slope of the height regression line indicates that the later emerging biochar plants grew fastest. The earlier the biochar-treated plants emerged the slower they grew, and the later the germination date the faster the growth rate. As a result, all treatments (control, three hour, six hour) were not significantly different in size at 30 days (Fig. 14). The slopes of the height regression lines (as shown in Fig. 13) significantly differed between the control and biochar treated plants. The biochar treated plants displayed regression lines that were significantly more positively correlated with the emergence date. The control height slope regression lines were not correlated with the emergence date. These were complex results due again to interaction effects.

DISCUSSION

The answer to my first question (Can food waste biochar be made into an effective fertilizer?) is a complicated 'no.' The biochar amended plants had later germination dates on average, but there were no significant differences in final height, final dry mass, or overall growth rate. The biochar, when compared to the plain control soil, did not make the plants grow faster on average or taller by the end of 30 days. As a fertilizer, this product would not be recommended based on these results. However, it was found that the later germinating biochar plants grew faster. The answer to my second question (Does the effect of biochar vary among batches of food waste or pyrolysis time?) was complicated by many interacting results. No conclusion can be made about the individual biochar batches without also specifying the pyrolysis treatment that the batch received; no conclusion could be made about the effect of pyrolysis time without also discussing the biochar batch of that treatment as well. Without assigning quality or significant patterns, it does appear that the properties of the biochar did vary in my study by batch.

Energy inputs for the three and six hour batches were relatively low. The Fisher Scientific Isotemp 725g Laboratory Oven is a 1300 kW, 120V oven. To pyrolyze at 260°C for three hours used 3.90 kWh of energy. At an average of \$0.12 per kWh, this is \$0.16 per hour or \$0.47 total spent on energy in each batch. This process released the same amount of greenhouse gases as driving a car for 10.3 km (6.4 miles). To pyrolyze at this temperature for six hours used 7.8 kWh of energy, and this cost \$0.94 per batch. This would release the same amount of greenhouse gases as driving a car for 20.6 km (12.8 miles).

Emergence Date

The mean emergence day of the control plants was earlier than the three and six hour treatments. Previous studies have found biochar can have different properties and can interact with different soil types in many ways. Sun et al. (2014) found that the production method had a strong effect on the biochar properties. Yet, across all methods, they did not find a significant effect on seed emergence and, thus, were able to use their biochar as a soil amendment. There are many variables in biochar production, and biochars with different properties can be developed by adjusting these production conditions to satisfy certain application needs (Sun et al 2014).

Similarly, other studies have found biochar has no effect on emergence. Free et al. (2010) examined early growth in maize seeds and found no evidence of biochar significantly affecting emergence. Further, there are no interactions between rate of biochar application or biochar type and soil type (Free et al 2010). Examining six different biochar feedstocks, Rogovska et al. (2012) found no effect of biochar on emergence. Though there were no

emergence effects seen, it was found that there are polycyclic aromatic hydrocarbons in the biochar soil extracts. The reduction seen in seedling growth in Rogovska et al. (2012) was attributed to the presence of these phytotoxic compounds. They concluded that emergence tests run with biochar would be a reliable method to assess the effect of biochar on seedling growth and biochar quality (Rogovska et al. 2012).

Unlike the findings of my study, Solaiman et al. (2012) saw an increase in percent seed emergence with addition of biochar. They found that lower rates of biochar application—about 10% by mass—increased wheat seed emergence. Though, at the highest rates of application—close to 100% by mass—there is a decrease or no effect on emergence of the seedlings. Furthermore, Solaiman et al. (2012) found that biochars can contain nutrients that can affect seed emergence. Concentrations of nutrients, from trace amounts to high levels, can be present in the product depending on the feedstock (Solaiman et al. 2012). There is greater effect on seed emergence and seedling growth in soils of lower fertility. The rate of application in my study was only five percent by mass, but combined with the very low fertility of the soil used, might still have affected the emergence of the tomato seedlings. Due to the presence of these emergence-inhibiting compounds, emergence tests could be useful as an assessment of the quality of biochars (Sun et al. 2014, Rogovska et al. 2012, Solaiman et al. 2012, Free et al. 2010).

The pyrolysis temperature or duration in my study may have produced biochar with poor seed-starting ability and the presence of inhibitory hydrocarbons. There was variation among batches in emergence date and interaction with both the three and six hour treatments, thus, no qualification of which of the batches or two treatment types was better could be made. In future comestible plant or crop application, emergence tests can be done to assess the viability and quality of the biochar as a fertilizing soil amendment. Moreover, some additional amendment may need to be added when using certain biochars to aid in improving emergence.

Height and Growth Rate

Due to interacting batch and treatment effects, it is not known if the differences in height at the end of the study were caused directly by emergence date or indirectly by biochar and its effect on growth rate (Fig. 15). However, due to significantly earlier emergence dates the control plants were taller at each day measured. Mean height growth rates were used to see the effect of biochar on growth rate compared to controls. The growth rate for all plants takes into account the effects of any emergence day and final height or dry mass differences between control and biochar plants. This revealed that the earlier the biochar plants emerged the faster the growth rate. There is some unknown effect of biochar on the plants. This caused the plants that emerged last to have a growth rate that was high enough to grow to final heights that were not significantly different than the control and earliest emerging

biochar plants by the end of the study. It was expected that growth rates would be the same regardless of emergence, so the later the emergence date the shorter the final height expected at 30 days. However, all treatments produced the same final height regardless of emergence. Growth rates may have been affected in different ways not measured by these analyses. There also may have been more pronounced differences had I grown these plants to maturity as well as assessed their ability to bear fruit.

As demonstrated earlier, nutrient availability as well as other biochar properties may have affected plant growth. Guereña et al. (2013) pyrolyzed at a much higher temperature (600°C) but found 410 ppm of phosphorus and only 2 ppm of nitrite nitrogen, with a pH of 10.02. These nutrients are in the same range as the biochar in my study (Table 3), but the pH is much higher in their product. This might mean their biochar would be better used to buffer more acidic soils; the biochar in my study might provide for better plant growth in different soil types. Similar effectiveness as an alkaline amendment was found in other studies utilizing dairy manure feedstock (Cao and Harris 2010). Lehmann et al. (2011) also observed an increase in soil fertility and plant growth that they explain mainly by a pH increase in acidic soils.

Use of algae as feedstock yields biochar that is high in nitrogen and phosphorus compared to a wood-based biomass, but it was found that these benefits tend to decrease as pyrolysis temperature increases (Bird et al. 2011). It is possible that the pyrolysis temperature used to produce my biochar had an effect on the nutrient content, or on the nutrient release capacity of the biochar causing the plants to grow at different rates based on batch. However, there were no significant differences between batches or treatments found in nutrient content or pH so this does not explain the growth rate differences in the earlier and later emerging biochar plants. Also, many studies have found that biochar addition increases crop yield and general biomass, but only if simultaneously applied with nitrogen fertilizer (Budai et al. 2014, Wang et al. 2012, Cox 2010). None note a differential growth rate depending on emergence date.

Budai et al. (2014) asserted that the high variability in soil conditions such as pH and composition complicate the use of different types of biochar added to soil to grow food. Som et al. (2013) used palm fronds as feedstock and found that the pH and cation exchange capacity values were high in their biochar product and proved effective slow-release fertilizers for tropical soils that receive heavy rainfall. The warm and moist greenhouse conditions in which my study was performed might have been similar to these tropical parameters and have caused the slow release of nutrients from the biochar seen in differential growth rates.

It has also been found that certain biochars improve nutrient retention through cation adsorption in the soils and limit the amount of fertilizers leached into runoff water (Budai et al. 2014, Liao et al. 2013, Lehmann et al. 2011). This might mean that the short growing window of my study was insufficient time for the release of nutrients from the biochar, and that on day 30 some of these slow-release benefits may have only just begun becoming evident. Longer plant growth time may be required to observe any other beneficial effects from all batches and treatments of the biochar when compared to the control plants.

Aboveground Dry Mass

Biochar did not significantly affect plant dry mass at 30 days in my study, but only aboveground dry mass was measured. Belowground biomass allocation may have been different in the biochar and control plants, and this might have been affected by certain properties of the biochar. Plants can change their biomass allocation in response to a decrease in certain resources with increased allocation into particular areas of the plant (Poorter and Nagel 2000). In this way, they alter the root to shoot biomass ratio following a pattern of functional equilibrium. Generally, plants respond to a decrease in belowground resources with increased biomass allocation into roots. Poorter and Nagel (2000) found that the plants response to available nutrients follows this functional equilibrium hypothesis. Pertaining to specifically biochar, Muller et al. (2000) found that biochar amended plants allocated less to aboveground mass (i.e. stems and leaves) in low-nutrient conditions than in soils of high nutrient concentration. The larger amounts of aboveground dry mass seen in some batches of my study but not others may have been affected by these growth conditions and the relatively low amount of available nutrients. Though this is hard to study accurately, had it been examined closer in my study, a different pattern may have emerged.

Biochar has been found to have certain agronomic functions that improve water retention in soils (Budai et al. 2014, Bird et al. 2011). In my study, improved access to water with the application of biochar may have helped the treated plants grow more quickly or have differential biomass allocation when compared to the non-amended control plants. The porous nature of the biochar particles allows them to have high surface areas which improves water-holding capacity and has beneficial effects on the microbial population as well as stimulating mycorrhizae fungal growth (Budai et al. 2014, Cox 2010, Lehmann et al. 2011, Bird et al. 2011, Renner 2007). All of these properties of biochar amended soil have been found to encourage root growth with biochar amendment (Stavi 2012, Renner 2007). My study did not measure any of these parameters of soil conditions or plant growth. However, further studies may address these topics of water-retention, microbial and mycorrhizal growth in the soil, and

biomass allocation to plant root growth as a result of this. More studies are needed to investigate these parameters as well as their interactions with each other.

Biochar had an effect on emergence date but not on final aboveground dry mass or average growth rate. There are many complex interactions in this study and much yet to learn about how individual batches of food waste biochar affect plant growth. The complex effects of biochar on emergence and growth rate suggest that growing plants to maturity may have demonstrated clear size effects. This might also allow for the biochar amended plants to yield the benefits and show signs of the slow-release fertilizing effect found in some biochar studies. Also, a further exploration of the interactions of soil properties with biochar application would be beneficial in future studies. Measurement of cation exchange capacity, microbial and mycorrhizal activity, and belowground biomass allocation might better explain the results found in my study. Further studies may also look to addressing the batch variation in feedstock type by controlling what types of food waste are used. This may help to address the complexity of the interactions that were seen in my study. Taking into account the type of food waste used and organizing the batches by certain types of food waste, the effect of particular types of waste as biochar feedstock could be examined. There may be nutritional superiority in certain food types as well as other differences seen in pH, salinity content, and water-holding capacity. The variability in the performance of different batches of biochar may be an impediment to small-scale homeowner production and biochar application as a fertilizing amendment.

The biochar did not appear to be an effective fertilizing soil amendment. There was a significant difference in germination time between the biochar and the control plants. The control plants emerged earlier than the biochar plants. At the end of the 30 growth days of the study, the biochar plants did not differ significantly from the control plants in height, final aboveground dry mass, or growth rate. Biochar did not improve the growth of the plants as would be expected with application of a fertilizer. However, the fact that the later germinating biochar plants showed no significant differences in height at the end of the study means that those that germinated last grew fastest. This is an interesting effect of biochar on plant growth and the cause for this effect needs to be studied further.

There were variations in the biochar based on batch and pyrolysis treatment. However, no final conclusions on quality can be stated from the results due to many complex interactions. The effect of batch interacted with the effect of pyrolysis time in different ways depending on the type of plant measurement analyzed. These interacting effects make any conclusion of which batch or pyrolysis treatment was superior impossible without specifying both batch and pyrolysis treatment.

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TABLES

Table 1. Composition of each batch listed in order of most abundant to least abundant in the source food waste for each given batch.

Batch #	Composition
1	Cauliflower stems, pineapple rind and leaf tops, potato peels, egg shells, banana peels, celery stalks
2	Watermelon rinds, corn husks, egg shells, banana peels
3	Potato peels, pineapple cores, cantaloupe rinds, carrot greens, capsicum seeds and stems, grape vines
4	Carrots, celery stalks

Table 2. Number of germinated plants in the four batches and three treatments of biochar.

	Batch				Treatment
	1	2	3	4	
3 hours	17	17	16	17	67
6 hours	16	16	17	11	60
Ctrl (no biochar)					65

Table 3. Nutrients by batch for control (plain soil), three hour, and six hour treatments.

Batch	Treatment (hour)	Chloride (ppm)	Phosphorus (ppm)	Nitrate nitrogen (ppm)	Potassium (ppm)	Nitrite nitrogen (ppm)	pH
1	3	100	200	75	400	5	8.0
	6	25	200	50	250	1	8.0
2	3	100	200	75	250	1	8.0
	6	25	200	75	300	5	8.0
3	3	100	200	10	300	5	8.0
	6	100	150	30	150	1	8.0
4	3	100	200	75	250	1	8.0
	6	50	150	50	250	5	8.0
Control	-	100	100	60	100	10	7.0

Table 4. Natural log transformed mean emergence date (± 1 SE) and sample size (n) by batch and treatment.

	3 hr	6 hr	Control	Batch
1	2.02 $\pm$ 0.224 (17)	2.01 $\pm$ 0.321 (16)		2.01 $\pm$ 0.271 (33)
2	2.16 $\pm$ 0.324 (17)	2.02 $\pm$ 0.236 (16)	-	2.09 $\pm$ 0.29 (33)
3	1.73 $\pm$ 0.106 (16)	1.73 $\pm$ 0.141 (17)		1.73 $\pm$ 0.123 (33)
4	1.71 $\pm$ 0.239 (17)	2.11 $\pm$ 0.611 (11)		1.87 $\pm$ 0.461 (28)
Trmt	1.91 $\pm$ 0.303 (67)	1.95 $\pm$ 0.361 (60)	1.36 $\pm$ 0.171 (65)	-

Table 5. Natural log transformed mean final dry mass in grams (± 1 SE) and sample size (n) by batch and treatment.

	3 hr	6 hr	Control	Batch
1	0.78 $\pm$ 0.569 (17)	0.07 $\pm$ 1.391 (16)		0.44 $\pm$ 1.094 (33)
2	0.46 $\pm$ 1.335 (17)	0.68 $\pm$ 0.369 (16)	-	0.57 $\pm$ 0.983 (33)
3	-1.91 $\pm$ 1.266 (16)	-1.02 $\pm$ 1.171 (17)		-1.45 $\pm$ 1.281 (33)
4	-1.3 $\pm$ 1.192 (17)	-1.41 $\pm$ 1.925 (11)		-1.24 $\pm$ 1.490 (28)
Trmt	-0.47 $\pm$ 1.589 (67)	-0.298 $\pm$ 1.451 (60)	-0.12 $\pm$ 0.742 (65)	-

Table 6. Mean growth rate in millimeters per day (± 1 SE) and sample size (n) by batch and treatment.

	3 hr	6 hr	Control	Batch
1	7.58 $\pm$ 2.096 (17)	6.79 $\pm$ 2.266 (16)		7.2 $\pm$ 2.183 (33)
2	8.49 $\pm$ 2.276 (17)	7.83 $\pm$ 1.197 (16)		8.17 $\pm$ 1.837 (33)
3	3.60 $\pm$ 2.356 (16)	5.29 $\pm$ 1.514 (17)	-	4.47 $\pm$ 2.118 (33)
4	5.34 $\pm$ 1.868 (17)	6.02 $\pm$ 2.032 (11)		5.59 $\pm$ 1.92 (28)
Trmt	6.29 $\pm$ 2.845 (67)	6.51 $\pm$ 1.987 (60)	6.08 $\pm$ 1.582 (65)	-



Fig. 1. Example measure of leaf canopy diameter (cm).

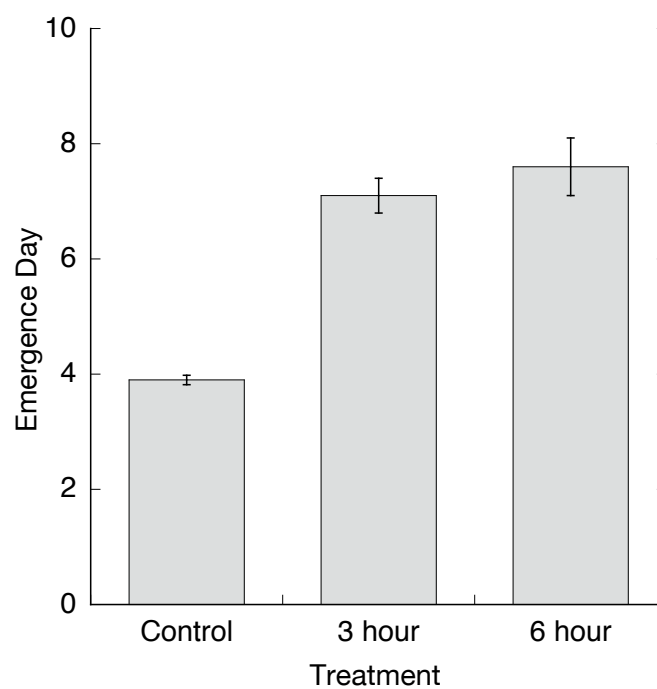


Fig. 2. Mean day of *Solanum lycopersicum* seedling emergence by treatment. Kruskal-Wallis Test: $p < 0.0001$, $\chi^2 = 114$, d.f. = 2. Error bars are ± 1 SE.

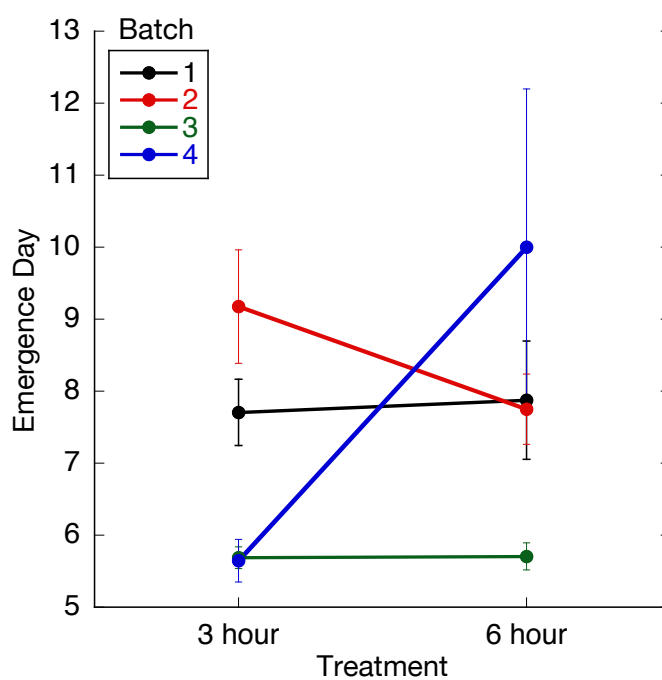


Fig. 3. Mean day of *Solanum lycopersicum* seedling emergence by batch. Analysis of variance: $p=0.003$, $F=4.8$, $d.f.=3, 119$. Error bars are ± 1 SE.

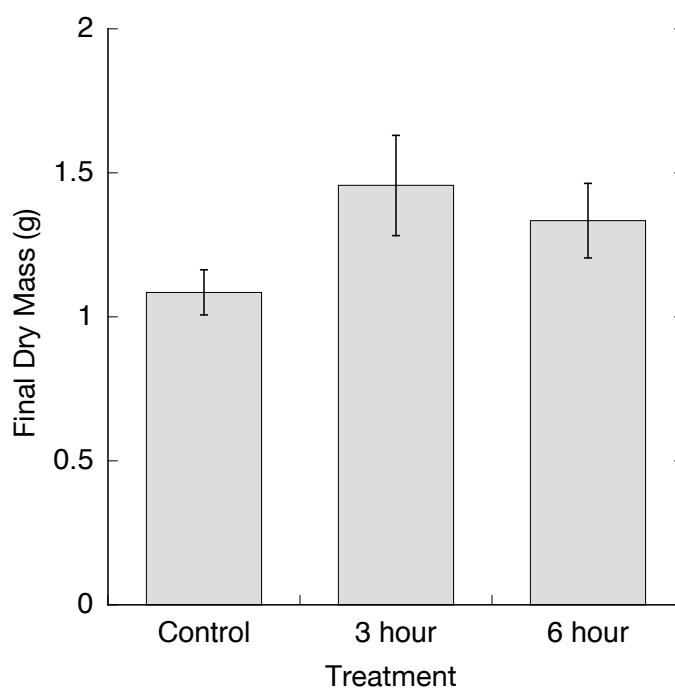


Fig. 4. Mean final dry mass (in grams) of *Solanum lycopersicum* by treatment. Kruskal-Wallis Test: $p=0.71$, $\chi^2=0.694$, $d.f.=2$. Error bars are ± 1 SE.

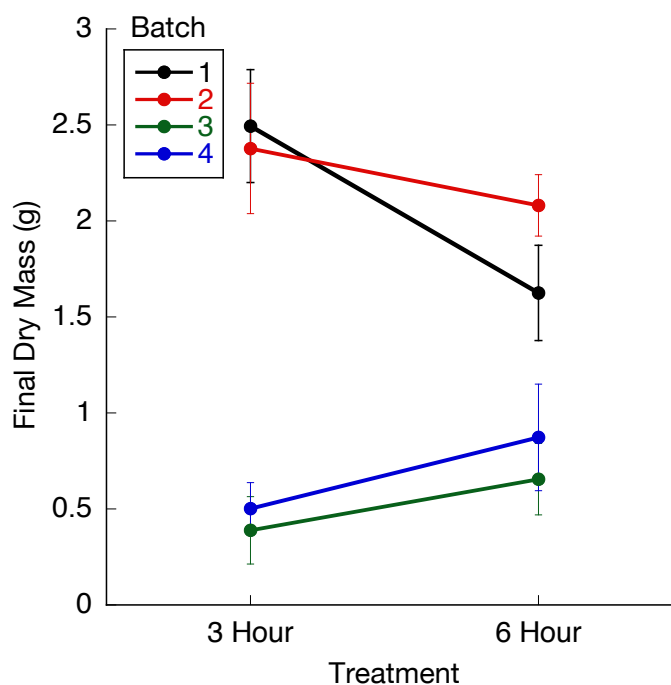


Fig. 5. Mean final dry mass (in grams) of *Solanum lycopersicum* by batch. Analysis of variance: $p = 0.065$, $F = 2.46$, $d.f. = 3, 119$. Error bars are ± 1 SE.

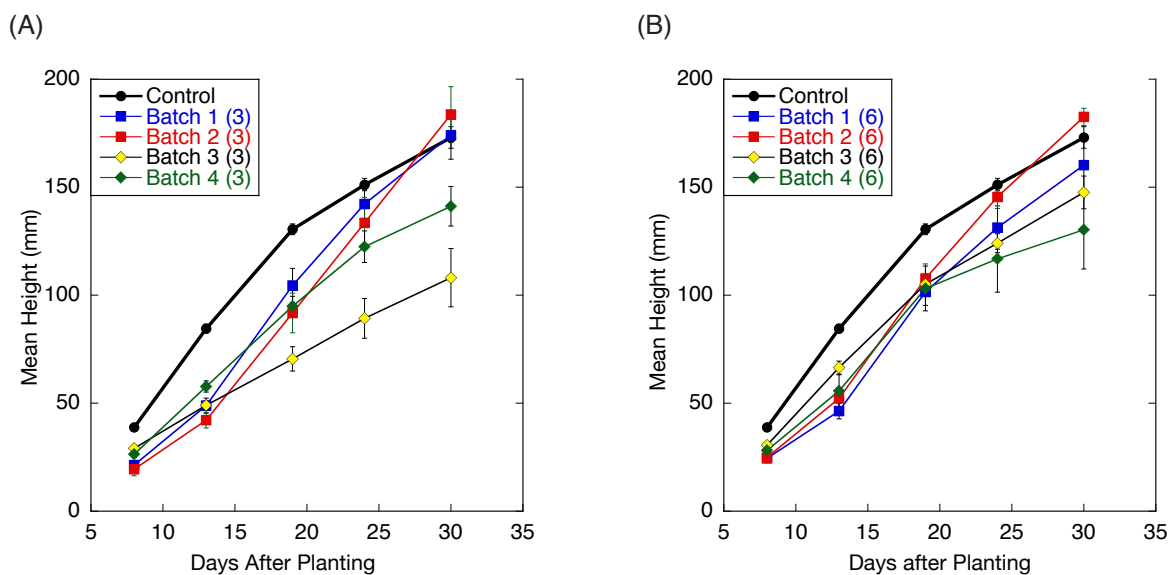


Fig. 6. (A) Relationship between mean height (mm) $\pm$ (1 SE) and days after planting of *Solanum lycopersicum* by batch for the three hour pyrolysis treatment. **(B)** Relationship between mean height (mm) $\pm$ (1 SE) and days after planting of *Solanum lycopersicum* by batch for the six hour pyrolysis treatment.

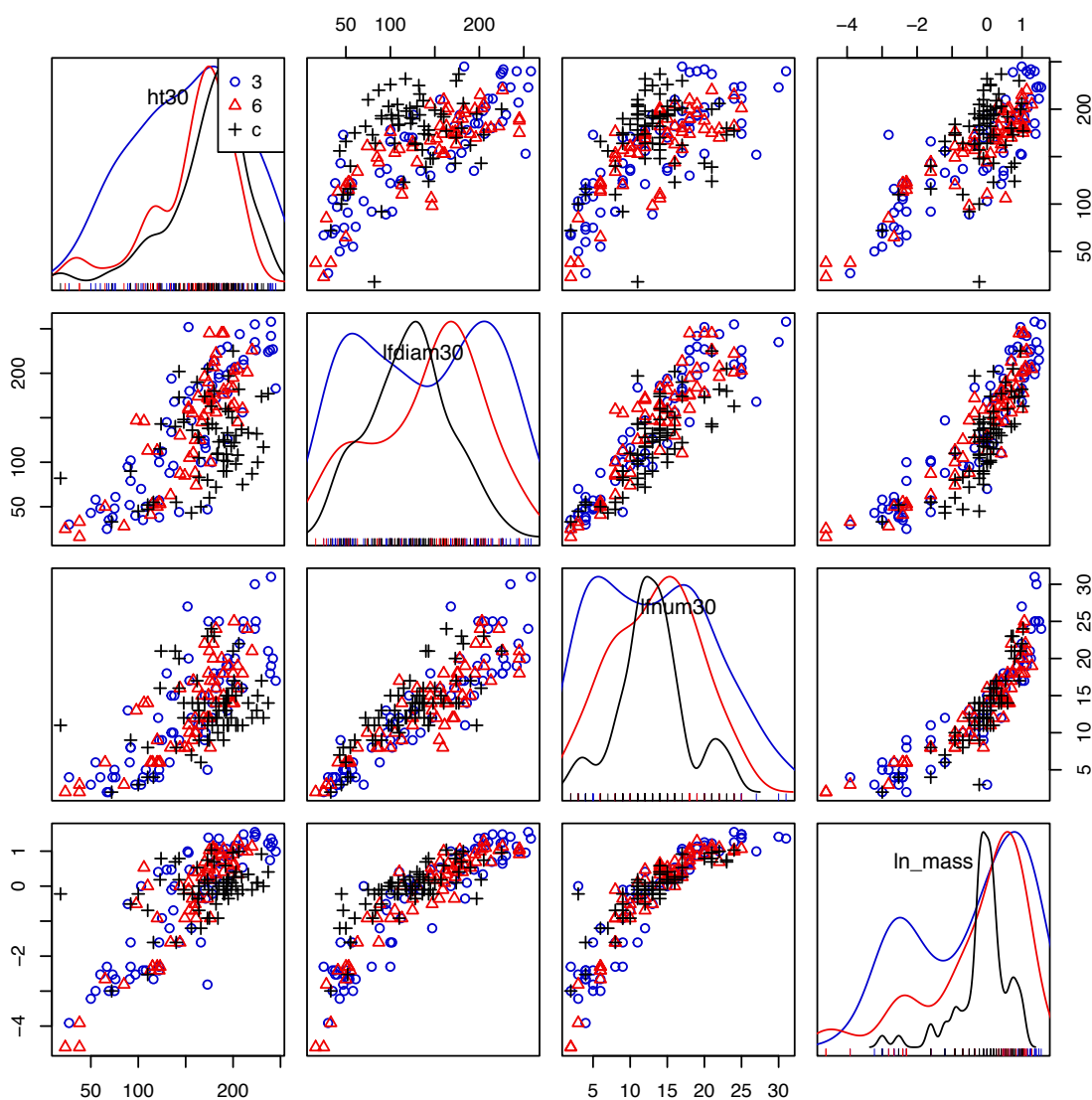


Fig. 7. Scatterplot matrix displaying relationships among plant height (ht30, mm), leaf canopy diameter (lfdiam30, mm), leaf number (lfnun30), and ln(final dry mass) (ln_mass, g) of *Solanum lycopersicum* on day 30, separated by treatment.

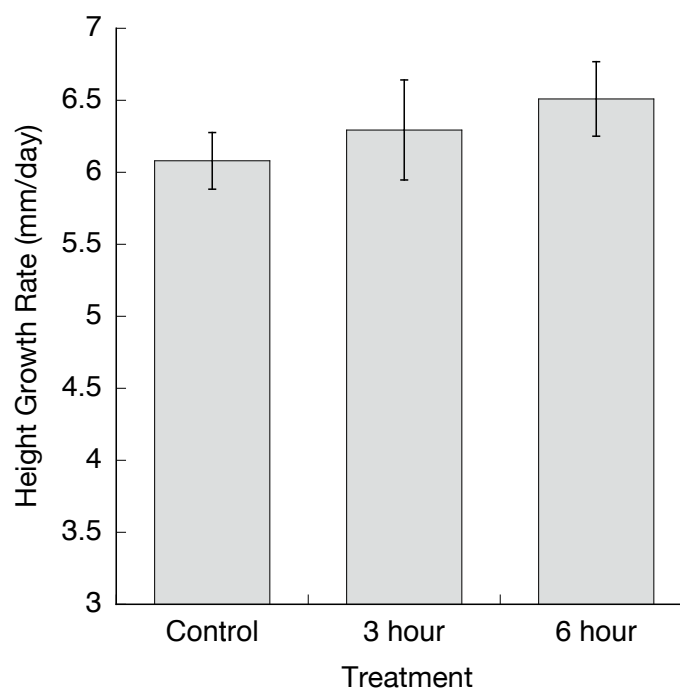


Fig. 8. Mean height growth rate (mm/day) of *Solanum lycopersicum* by treatment. Analysis of variance: $p=0.56$, $F=0.582$, $d.f.=2, 188$. Error bars are ± 1 SE.

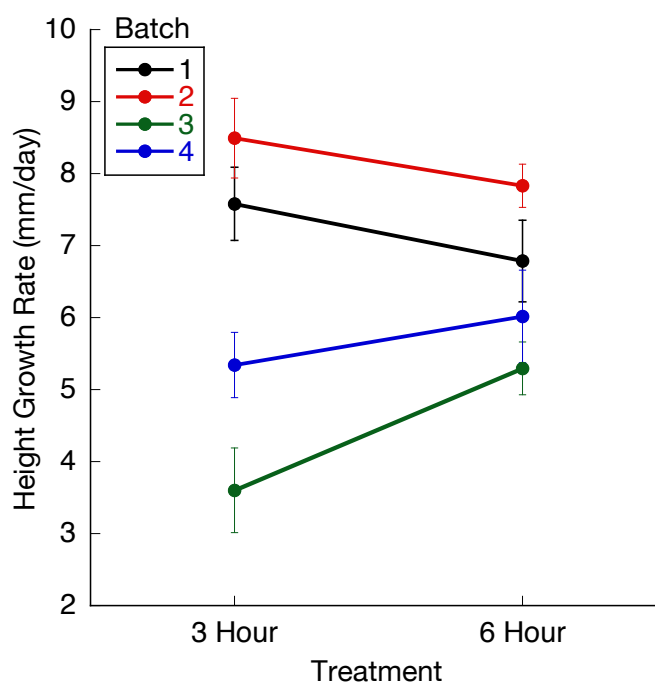


Fig. 9. Mean height growth rate (mm/day) of *Solanum lycopersicum* by batch. Analysis of variance: $p=0.039$, $F=2.88$, $d.f.=3, 118$. Error bars are ± 1 SE.

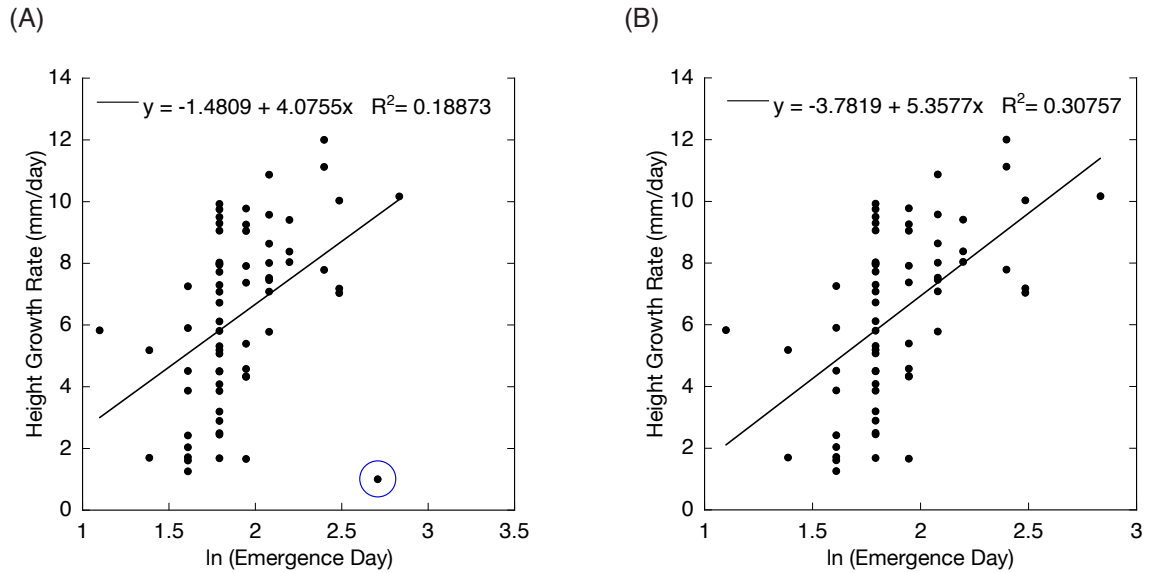


Fig. 10. (A) Relationship between $\ln(\text{Emergence Day})$ and slope of the height growth rate regression for three hour treatment. Circled point: outlier removed for analysis. **(B)** Relationship between $\ln(\text{Emergence Day})$ and slope of the height growth rate regression for three hour treatment with one outlier removed. The r^2 increased from 0.19 to 0.31 after removal of the outlier.

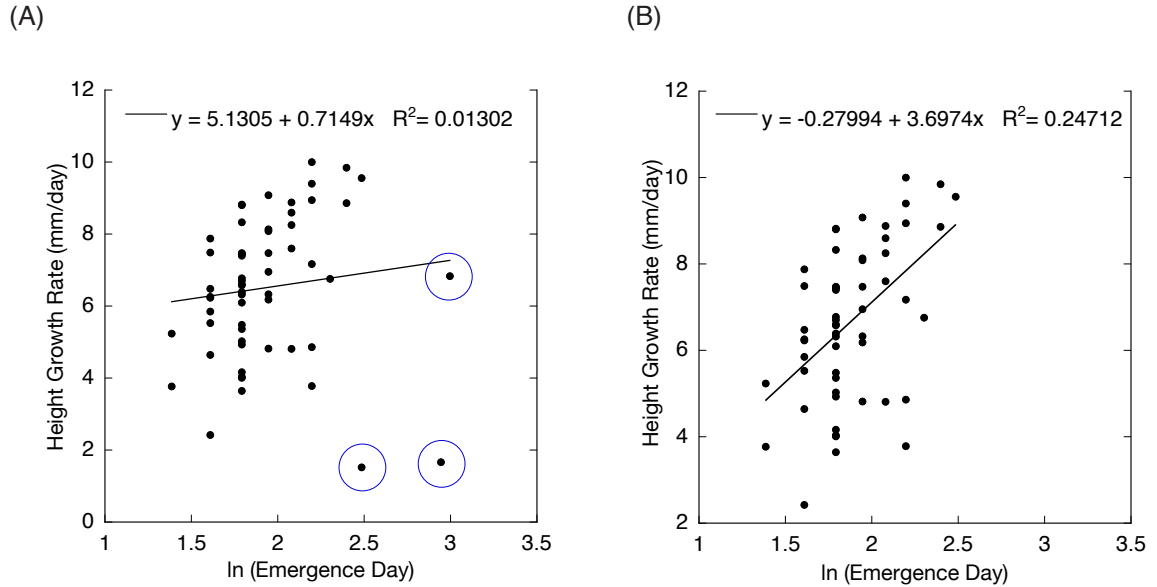


Fig. 11. (A) Relationship between $\ln(\text{Emergence Day})$ and slope of the height growth rate regression for six hour treatment. Circled points: outliers removed for analysis. **(B)** Relationship between $\ln(\text{Emergence Day})$ and slope of the height growth rate regression for six hour treatment with three outliers removed. The r^2 increased from 0.013 to 0.25 after removal of the outliers.

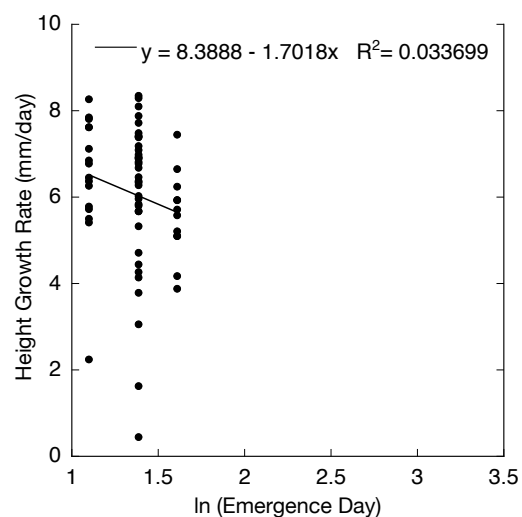


Fig. 12. Relationship between $\ln(\text{Emergence Day})$ and slope of the height growth rate regression for control treatment. No outliers removed.

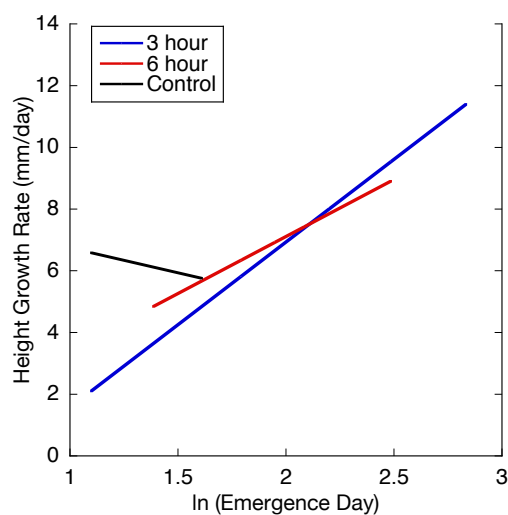


Fig. 13. Relationship between height growth rate (mm/day) and $\ln(\text{Emergence Day})$ of *Solanum lycopersicum* for three hour [height growth rate = $-3.7819 + 5.3577x$, $r^2 = 0.308$], six hour [height growth rate = $1.5018 + 2.724x$, $r^2 = 0.185$], and control [height growth rate = $8.3539 - 1.6118x$, $r^2 = 0.038$].

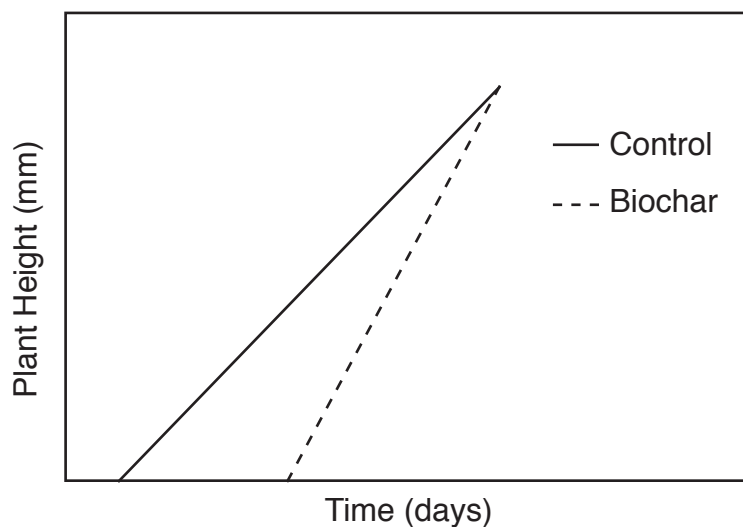


Fig. 14. Control plants germinated earlier than biochar plants. All treatments had the same final height due to later germinating biochar plants growing faster than earlier germinating biochar and control plants.

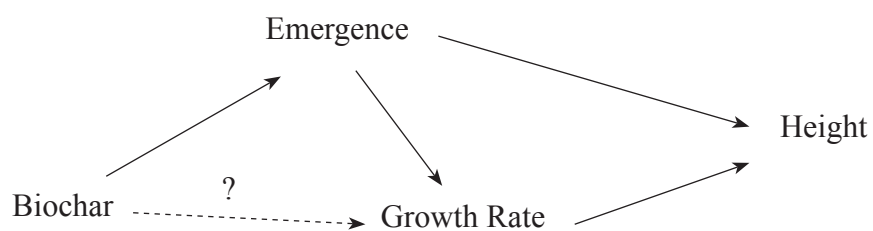


Fig. 15. Pathway of interacting effects of biochar on emergence and growth rate and their effects on plant height. Question mark indicating an unknown direct effect of biochar on growth rate and indirect effect on height.

APPENDIX A - Photos

Fig. A1. Sample food waste collection for one batch.



Fig. A2. Chopped food waste in trays.



Fig. A3. Fine mesh used in air drying.



Fig. A4. Dried food material before pyrolysis (left) and after (right) in the CorningWare casserole dish.



Fig. A5. Fine biochar power, final product after being pulverized.



Fig. A6. Tomato Seedling Shoots.



Fig. A7. 204 plant growth set up in greenhouse.



Fig. A8. Left: Potting medium comparison; control soil at day 30 (left), biochar amended soil at day 30 (right). **Right:** Aboveground final dry mass; control plant (left), three hour pyrolyzed biochar, batch 1 (middle), six hour pyrolyzed biochar, batch 1 (right).

APPENDIX B – Statistics

Table A1. ANOVA results for log transformed emergence date by batch, three or six hour pyrolysis (*treat*), and batch-treatment interaction (*batch:treat*).

	eta.sq	eta.sq.part	SS	df	MS	F	p
batch	0.182694432	0.201200651	2.5216578	3	0.84055260	9.9911939	6.351931e-06
treat	0.004779216	0.006545922	0.0659656	1	0.06596560	0.7840974	3.776768e-01
batch:treat	0.087456262	0.107601010	1.2071236	3	0.40237454	4.7828084	3.497891e-03
Residuals	0.725326643	NA	10.0113920	119	0.08412934	NA	NA

Table A2. ANOVA results for log transformed emergence date by treatment (controls, three hour, and six hour).

	eta.sq	eta.sq.part	SS	df	MS	F	p
treat	0.4752228	0.4752228	14.13129	2	7.06564489	85.57643	0
Residuals	0.5247772	NA	15.60484	189	0.08256532	NA	NA

Table A3. ANOVA results for log transformed final dry mass in grams by batch, three or six hour pyrolysis (*treat*), and batch-treatment interaction (*batch:treat*).

	eta.sq	eta.sq.part	SS	df	MS	F	p
batch	0.375966973	0.391407224	109.6966552	3	36.5655517	25.5110157	8.160139e-13
treat	0.002072892	0.003533392	0.6048119	1	0.6048119	0.4219646	5.172103e-01
batch:treat	0.036182914	0.058287347	10.5571630	3	3.5190543	2.4551701	6.648497e-02
Residuals	0.584584979	NA	170.5655588	119	1.4333240	NA	NA

Table A4. ANOVA results for log transformed final dry mass in grams by treatment (controls, three hour, and six hour).

	eta.sq	eta.sq.part	SS	df	MS	F	p
treat	0.01212614	0.01212614	4.002698	2	2.001349	1.159986	0.3157122
Residuals	0.98787386	NA	326.085792	189	1.725322	NA	NA

Table A5. ANOVA results for log transformed growth rate in millimeters per day by batch, three or six hour pyrolysis (*treat*), and batch-treatment interaction (*batch:treat*).

	eta.sq	eta.sq.part	SS	df	MS	F	p
batch	0.345901409	0.362755345	264.467768	3	88.155923	22.390736	1.516087e-11
treat	0.001625493	0.002667965	1.242812	1	1.242812	0.315662	5.752920e-01
batch:treat	0.044550648	0.068309482	34.062337	3	11.354112	2.883833	3.870623e-02
Residuals	0.607637701	NA	464.584944	118	3.937161	NA	NA

Table A6. ANOVA results for growth rate in millimeters per day by treatment (controls, three hour, and six hour).

	eta.sq	eta.sq.part	SS	df	MS	F	p
treat	0.00615478	0.00615478	5.718359	2	2.859179	0.5821322	0.5597097
Residuals	0.99384522	NA	923.373946	188	4.911564	NA	NA

Table A7. ANOVA results for growth rate in millimeters per day by log transformed emergence date (*ln_emerg*), three or six hour pyrolysis (*treat*), and emergence date-treatment interaction (*ln_emerg:treat*).

	eta.sq	eta.sq.part	SS	df	MS	F	p
ln_emerg	0.05174825	0.05575779	48.07890	1	48.078900	10.924306	0.001139833
treat	0.01374744	0.01544502	12.77264	2	6.386321	1.451076	0.236972360
ln_emerg:treat	0.06575519	0.06979662	61.09264	2	30.546320	6.940620	0.001240100
Residuals	0.87634178	NA	814.20241	185	4.401094	NA	NA